WATER SUPPLY PLANNING FOR THE BI-NATIONAL REGION OF NOGALES, SONORA AND ARIZONA

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Introduction

The population of Nogales, Sonora, has increased dramatically in the last two decades from approximately 50,000 to 230,000 today. During the same time, Nogales, Arizona has doubled its population to about 20,000. Thus, the area has a total population of a quarter of a million people, plus a significant transient population as evidenced by the number of border crossings, which runs between 8 and 10 million per year.

The rapidly growing population has placed an ever-increasing burden on such common renewable resources as water. Effective planning in an expanding region requires knowledge on the limitations to expansion. As both cities tap the same aquifer, information is needed on the replenishment potential of this source of water. This paper addresses the water supply problem by presenting an approach for determining annual ground water recharge to the aquifer which indicates the capability of the water source to yield water on a sustaining basis. In addition, an estimate of recharge is important environmentally as this is the mechanism by which pollutants on the surface are transported into ground water sources.

An event-based methodology of ground water recharge from an ephemeral stream was first proposed by Fogel et al. (1976). This was elaborated by Flug et al. (1980) who used the Rillito Creek of the Tucson Basin as a case study. This study has concentrated on the upper reaches of the Santa Cruz River System in the vicinity of Nogales.

A number of studies have pointed out the water shortages in the upper Santa Cruz River Basin and the necessity for additional water development programs to satisfy the growing needs of the Twin Cities of Nogales (Halpenny, 1964, 1971; U.S. Bureau of Reclamation, 1965; Harshbarger, 1975 and Montano, 1981). None of these studies, however, have specified what is the available supply or placed any limits on the growth that may take place in the area based on the long-term availability of renewable resources.
The Santa Cruz Basin Near Nogales

The Upper Santa Cruz River in the vicinity of the border cities of Ambos Nogales starts in Arizona, runs south for a little ways into Mexico, turns west and then heads north back into Arizona. Located principally in the main stream channel and its major tributaries are the saturated permeable materials that yield significant quantities of water. In the Nogales area, the main stem aquifer is relatively thin and shallow as compared to that downstream, such as in the Tucson area, for example. These ground water reservoirs are replenished by infiltration of runoff that reaches the main stream channels and by recharge along the mountain fronts.

Pumping records on both sides of the border indicate that daily consumption per capita are about twice as high on the U.S. side as on the Mexican side. Per capita use in Nogales, Arizona is comparable to that of Tucson, Arizona, that is, about 160 gallon per day which is considerably less than what Phoenix uses.

Population projections for the area are lightly uncertain. The Arizona side is projected to double its population in the next 20 years. If this rate of growth occurs on the Mexican side of the border which is considerably less than recent records indicate, there appears to be no question that the water supply problem will become acute by that time.

There is another aspect to the problem. Pollution from surface sources may tend to limit the use of some portion of the aquifers or may necessitate the need for water treatment plants. Current potential sources of contamination include effluents from some of the twin-plant industries, the Nogales wash area and downstream from the international waste water treatment plant.

Ground Water Recharge Models

It is well established that ground water recharge in an ephemeral river system is a function of primarily (1) channel geometry (2) depth of water in the channel and (3) hydraulic conductivity of the surrounding materials. In an investigation of some simple models of groundwater recharge for ephemeral streams, Dillon (1981) suggested the use of both steady state and transient (non-steady) models where data are limited, which is the case for the study at hand. The steady state model that appears applicable for segments of the Santa Cruz River is

\[ q_r = K_{sat} (W_s + A Y) \]  

(1)
where

\[ q_r = \text{recharge rate per unit length of stream} \]
\[ K_{\text{sat}} = \text{saturated hydraulic conductivity of underlying material} \]
\[ W_s = \text{width of stream} \]
\[ A = \text{a parameter that is channel geometry dependent} \]
\[ Y = \text{depth of water in a stream} \]

For broad streams where flow depths are relatively shallow, the depth can be related to streamflow by the well-known formula

\[ q_s = aY^n \]  \hspace{1cm} (2)

where \( a \) is streamflow per unit width, \( a \) is a parameter dependent on stream gradient and retardance and \( n \) is either 5/3 or 3/2 dependent on whether Manning's or Chezy's flow formula is used. Thus, the volume of recharge is a function principally of the variables streamflow rate and duration and the site parameters channel geometry and hydraulic conductivity of the materials underlying the streambed.

Dillon also investigated transient models and made use of infiltration equations to determine the transient recharge. Using studies made by Bouwer (1969) and Philip (1969), he proposed a Philip-like equation for non-steady state recharge, namely,

\[ q_r/W_s = At^{-1/2} + C \]  \hspace{1cm} (3)

where \( A \) is a constant related to sorptivity and \( C \) is a constant representing the steady state recharge rate.

**Event-Based Methodology**

Streamflow in the Santa Cruz River system is decisely ephemeral in nature, that is, the river flows only in response to a precipitation event. As mentioned earlier, ground water recharge occurs when there is surface flow in the stream beds, which makes recharge decisely an event-based occurrence. In these ephemeral systems, the most important factor affecting the recharge to an underlying aquifer is the flow duration (Flug et al., 1980). Also considered as important factors are channel geometry, the volume of runoff and the hydraulic conductivity of surrounding materials.

As a first step towards developing an event-based model, the channel geometry and the hydraulic conductivity may be considered constant. However, the volume of flow has to be considered as this determines the depth of flow, which in turn, delineates the wetted perimeter or recharge surface. Thus, the flow variables of interest to ground water recharge are surface flow duration, magnitude of flow and time between events, which is similar to the event-based
methodology developed for precipitation events (Duckstein et al., 1972; Fogel et al., 1974; Davis et al., 1975).

Using the above methodology, the first step is to define an event. For this purpose, an event is defined as one for which daily streamflow exceeded a predetermined threshold value for one or more consecutive days. Streamflow below the threshold is deemed to have little recharge potential. Then, probability distributors are obtained for the number of events per season or year (N), the flow duration per event in days (D) and the interarrival time between events (T).

Previous studies (Kisiel et al., 1971; Duckstein et al., 1972) have indicated that runoff events occur independently, primarily for summer storms. The same is true for winter storm groups as defined by Duckstein et al. (1975). Thus, as described herein, a Poisson distribution can be used to describe the number of flow events in a given time period, that is,

\[ F_N(n) = \frac{e^{-m}m^n}{n!} \quad n=0,1,2... \quad (4) \]

where

\[ F_N(n) = \text{the probability density function (pdf) of the random variable } N \text{ for which } n \text{ is the dummy variable} \]

\[ m = \text{a statistical parameter} \]

In a study of the ephemeral winter-season flow in a small tributary in the Tucson Basin, Kisiel et al. (1971) found that streamflow duration can be described by a negative binomial distribution. A special case of this pdf is a geometric distribution which was used by Flug et al. (1980) for Rillito Creek streamflow duration, and can be written as follows:

\[ F_D(d) = (1-p)p^d \quad d=0,1,2... \quad (5) \]

where

\[ f_D(d) = \text{the probability density function for streamflow duration in days} \]

\[ p = \text{a statistical parameter} \]

Continuing with the precipitation analogy for the event-based approach to ground water recharge, the distribution function for the random variable D must be transformed into one for R, recharge. This can be done using Equation 3, the one for non-steady state recharge. The change of random variable is accomplished by solving Equation 3 for the dummy variable expressing time d in terms of r, the one for
recharge, or
\[ d = \left[ \frac{A}{r - C} \right]^\frac{1}{2} \]  
(6)

then, since
\[ F_R(r) = F_D[d(r)] \]
\[ F_R(r) = F_D\left[ \left( \frac{A}{r - C} \right)^\frac{1}{2} \right] \]  
(7)

This, then is the distribution function for recharge conditioned on the occurrence of a runoff event. However, since interest is in determining annual or seasonal recharge rather than recharge per event, the problem becomes one which can be considered as the sum of a random number of random variables. Assuming that the two variables \( N \) and \( R \) are in fact independent, then the total annual recharge, \( R_T \) is simply
\[ R_T = R(1) + R(2) + \cdots + R(N) \]  
(8)

while the distribution function for the variable \( R_T \) can be calculated from the distribution for \( R \) and \( N \), a much simpler approach is to compute the mean and the variance for \( R_T \). If the mean and variance of \( R \) and \( N \) are known or can be estimated from data, then the expected value or mean of \( R_T \) is
\[ E(R_T) = E(R) \cdot E(N) \]  
(9)

and the variance (VAR) is
\[ \text{VAR}(R_T) = \text{VAR}(R) \cdot E(N) + \text{VAR}(N) \cdot [E(R)]^2 \]  
(10)

Then, assuming a two-parameter probability distribution, e.g., log-normal, extreme value, or gamma, recharge values for any frequency or return period can be determined graphically or calculated using the results from Equations 9 and 10.

**Results and Discussion**

In reviewing the daily streamflow data for the Santa Cruz River at Nogales, steady flow rates for an extended number of days may occur usually during the winter months. At such times, the discharge is generally less than 10 cfs, which may indicate that the adjacent water table is feeding the river instead of surface water being supplied to the ground water. As a first estimate, a threshold value of 5 cfs was selected in defining a recharge event. That is, a daily flow below 5 cfs was assumed to have little recharge potential either because the recharge surface was relatively small compared to that for larger flows or that the reverse of ground water recharge was taking place. With this definition for a recharge event, distributions were obtained
for the number of events per year, the duration per event and the time between events.

With an event defined as a run of consecutive days in which daily streamflow exceeded 5 cfs, the number of events per year ranged from 3 to 10 with a mean of 6.5. A Poisson distribution (Eq. 4) was found to provide an acceptable fit to the data which was reinforced when it was determined that the interarrival times between events could be approximately by an exponential distribution. This is similar to the results obtained by Flug et al. (1980) for the Rillito Creek in the Tucson Basin.

Using the above definition for a recharge event, a geometric distribution (Eq. 5) was used to described streamflow duration. By the method of moments, the parameter p was estimated to be 0.58 which is comparable to the 0.53 found by Flug et al. (1980) for Rillito Creek. While a geometric pdf is acceptable, a two-parameter distribution such as the negative binomial as suggested by Kisiel et al. (1971) would provide a better fit particularly for the tail of the distribution.

As no information was available on the hydraulic characteristics of the Santa Cruz River streambed, this study could not be concluded with quantifiable results. In addition, to verify any such approach would require the existence of well data for a selected recharge area. Unfortunately, this data was also not available at the time of the study. This study, however, does present an approach to predicting ground water recharge to a shallow alluvial aquifer from an ephemeral stream using streamflow data, channel geometry and infiltration characteristics of the streambed.

Additional Research Needed

On site studies are needed to determine the infiltration characteristics of the Santa Cruz River streambed for both the steady and transient states, such as the saturated hydraulic conductivity, the sorptivity or related parameters.

Additional studies would also be needed to look into the possibility of separating summer recharge events from winter ones as was done by Flug et al. (1980). This could mean defining the events differently for each season which was the technique used for the event-based precipitation model developed earlier (Fogel et al., 1976).

Finally, some means for verifying the results would be very beneficial. Observation wells in the recharge area would be an effective technique for this function.
References Cited


Halpenny, L. 1971. Letter to Board of Supervisors, Santa Cruz County, Nogales, Arizona. Filed in Nogales City Hall, Arizona.


